Synoptic Sky Surveys and Exploration of the Time Domain

S. G. Djorgovski
(Caltech)

In collaboration with:

A. Mahabal, R. Williams,
A. Drake, M. Graham,
C. Donalek, E. Glikman,
the PQ and CSS survey teams

**The Great Surveys Workshop,
Santa Fe, Nov. 2008**

Time Domain Astrophysics

- **Moving objects:** Solar system, Galactic structure, exoplanets
- **Variability**
  - Intrinsic
  - Modulation along the LOS: microlensing, ISS, eclipses, variable extinction …

Physical causes of intrinsic variability:
  – Evolution: structural changes etc., long time scales
  – Internal processes, e.g., turbulence inside stars
  – Accretion/collapse: protostars, CVs, GRBs, QSOs
  – Thermonuclear explosions (SNe)
  – Magnetic field reconnections, e.g., stellar flares
  – Line of sight changes (rotation, jet instabilities…)

A broad, diverse range of interesting physics

Variability is known on time scales from ms to 10^{10} yr

> **Synoptic, panoramic surveys ➡ event discovery**
>
> **Rapid follow-up and multi-λ ➡ keys to understanding**

Dwarf Planets, Killer Rocks, and Snowballs

Dwarf planets and KBOs

M. Brown et al.

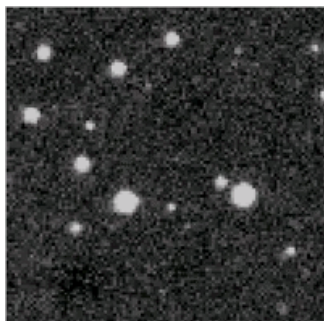Quauar

Sedna, Xena, … ?

NEAT, Catalina, PanSTARRS, etc.
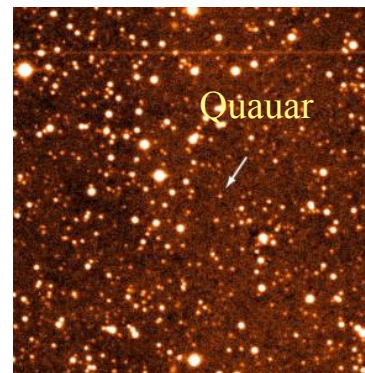
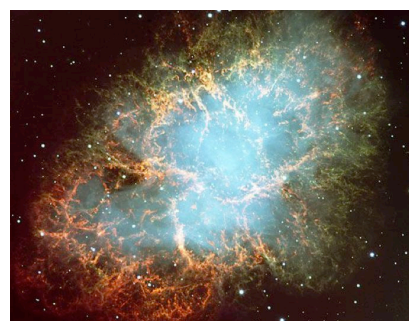Planetary Hazard Asteroids

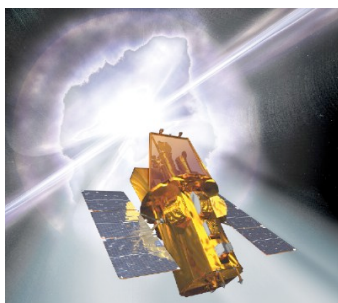Tunguska

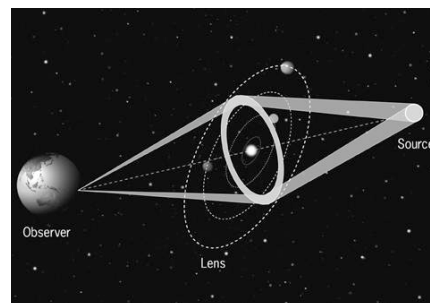# A Broad Variety of Phenomena

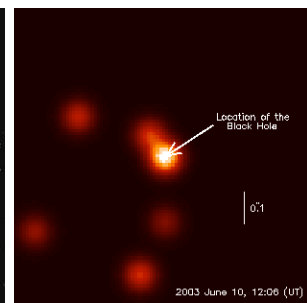Flaring stars

Novae, Cataclysmic Variables
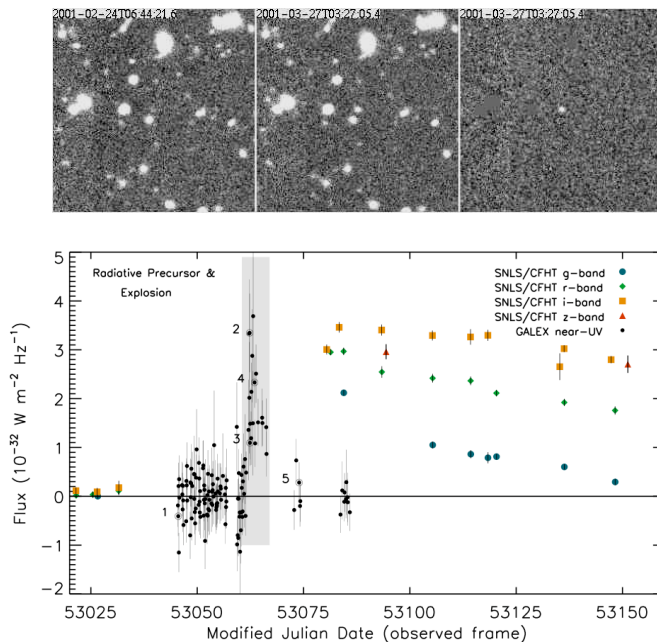

Supernovae

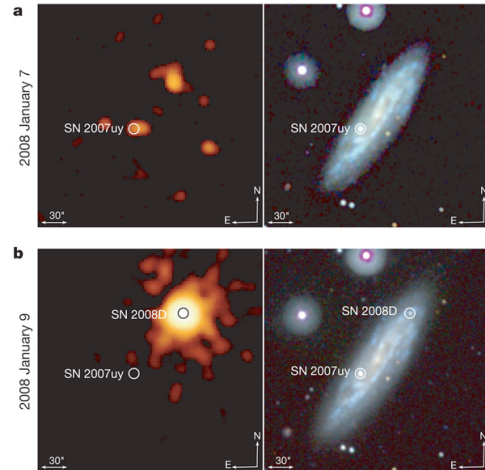Gamma-Ray Bursts

Gravitational Microlensing

Accretion to SMBHs

Supernova Breakout Shocks

Long anticipated, but just recently discovered *(Soderberg et al. 2008, Schawinski et al. 2008, Gezari et al. 2008, Modjaz et al. 2008)*
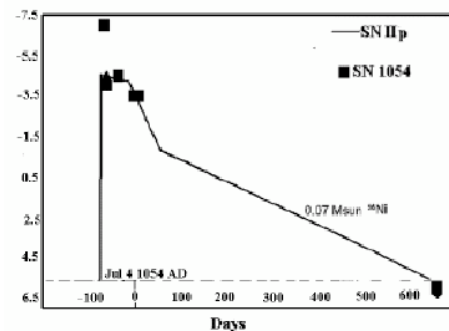
← Possibly seen in DLS, and other surveys?

… Recently?

# An Archival Detection of a SN II Flare in SN 1054?

Polcaro & Martocchia 2005, astro-ph/0511187: An archival record from *Tractatus de Ecclesia S. Petri Aldenburgensi*, by anonymous monk:

And the most blessed Pope Leo … on the 18th day before the first of May [i.e., 11 April 1054], a Monday, around midday, happily departed this world.   And at the same hour as his leaving of the flesh, not only in Rome, where his body lies, but also ***all over the world there appeared to men a circle in the sky of extraordinary brightness which lasted for about half an hour.***   Perhaps the Lord wished to say that he [the Pope] was worthy to receive a crown in Heaven between those who love Him.
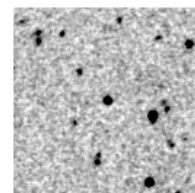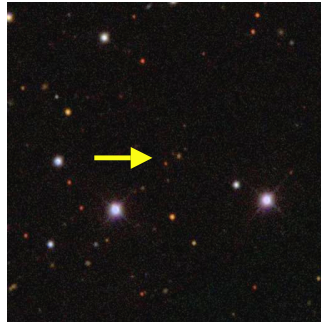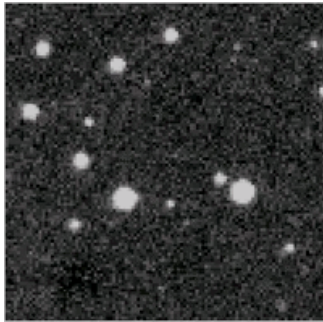
Flaring M Dwarfs

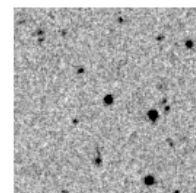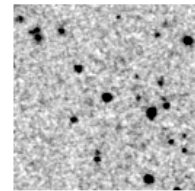(just like the Solar flares, but much, much bigger)
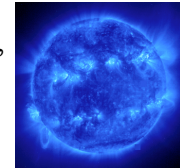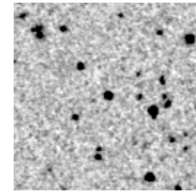
Lynx OT (CSS)   SDSS Counterpart

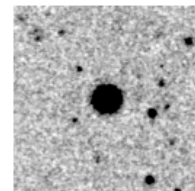## Super-flares from normal (~ Solar type) stars ➜

The cause(s), duration, and frequency of these outbursts are currently **unknown**

J

1988.3697   1988.4487

F

1991.2723   1994.3679

N

1990.1793   1997.3408

Accretion Flares From Otherwise Quiescent SMBHs

Tidal disruption of passing-by stars, and fallback. Expected rate $\sim 10^{-4}$ /galaxy/yr, $L_{peak} \sim 10^{44}$ erg/s

Komossa et al. (Rosat)
5 candidate events in X-rays

NGC 5905
○ ROSAT
● Chandra

$t^{-5/3}$

$L_X(0.1-2.4 \text{ keV})$ (ergs s^{-1})

Starburst Emission

Nucleus

Years since 1990.40
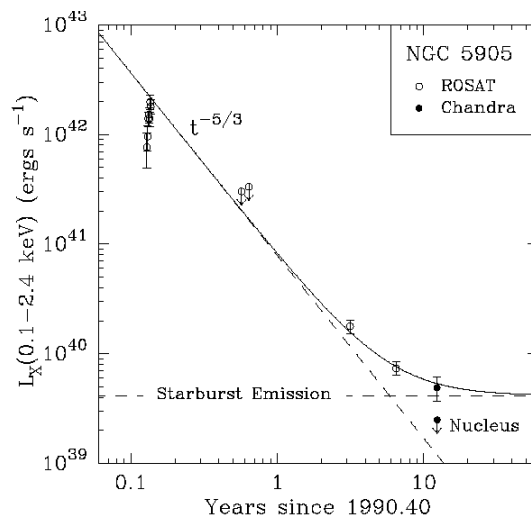
Gezari et al. (GALEX)
A few candidate events in UV

Magnitude

No Optical Var.

○ NUV
□ FUV

Year
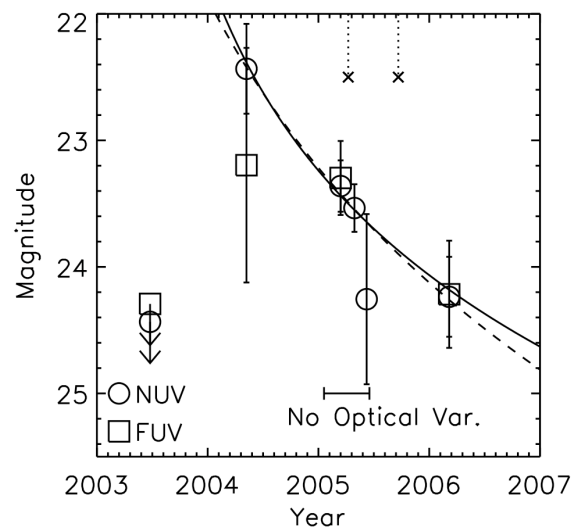
Accretion flicker from the
SMBH in our own Galaxy:

(Ghez et al., Keck)
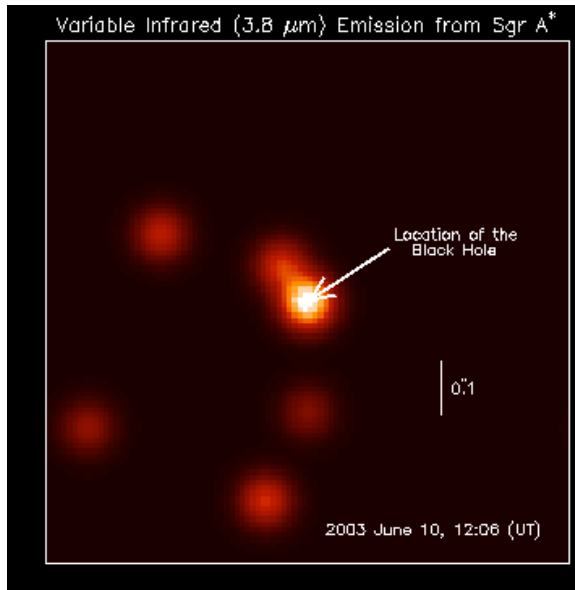
Variable sources in the
centers of apparently normal
galaxies at $z \sim$ few tenths:

(Totani et al., SUBARU)

Examples of Archival DPOSS Transients

(B. Granett et al.)
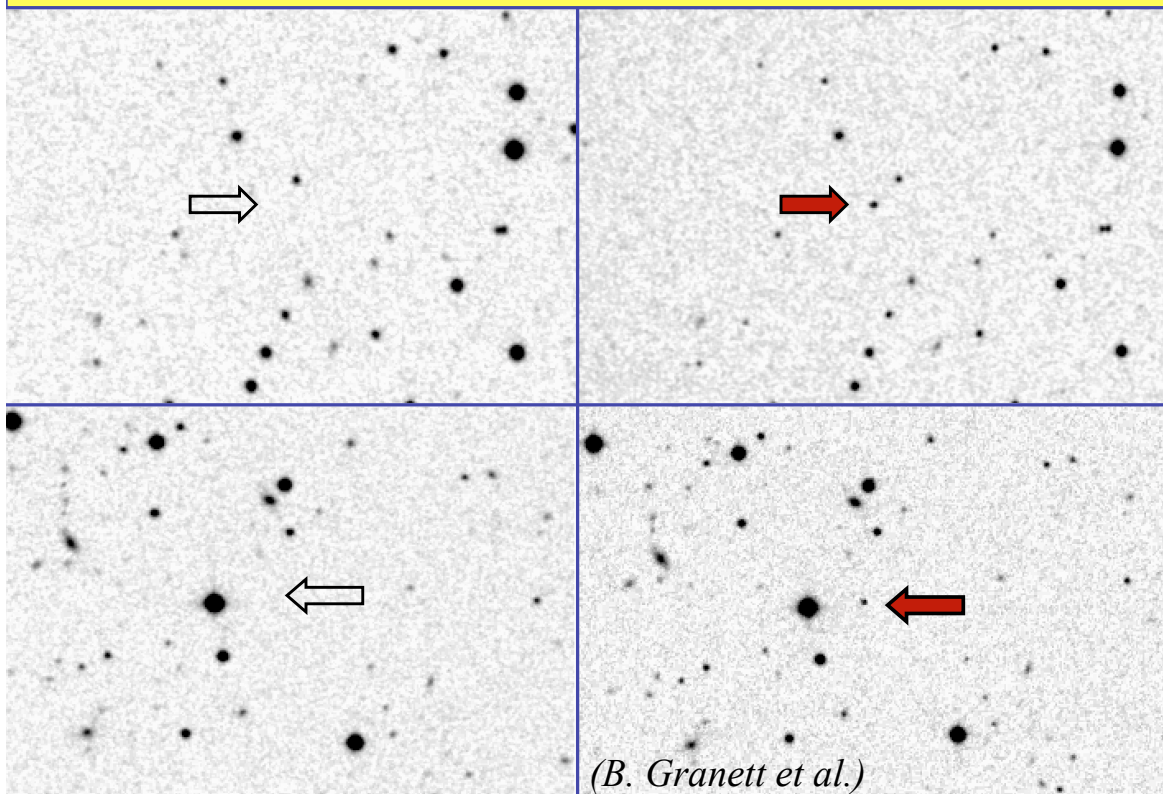
Unidentified Archival Transients in PQ

| | t_1 | t_2 | t_3 |
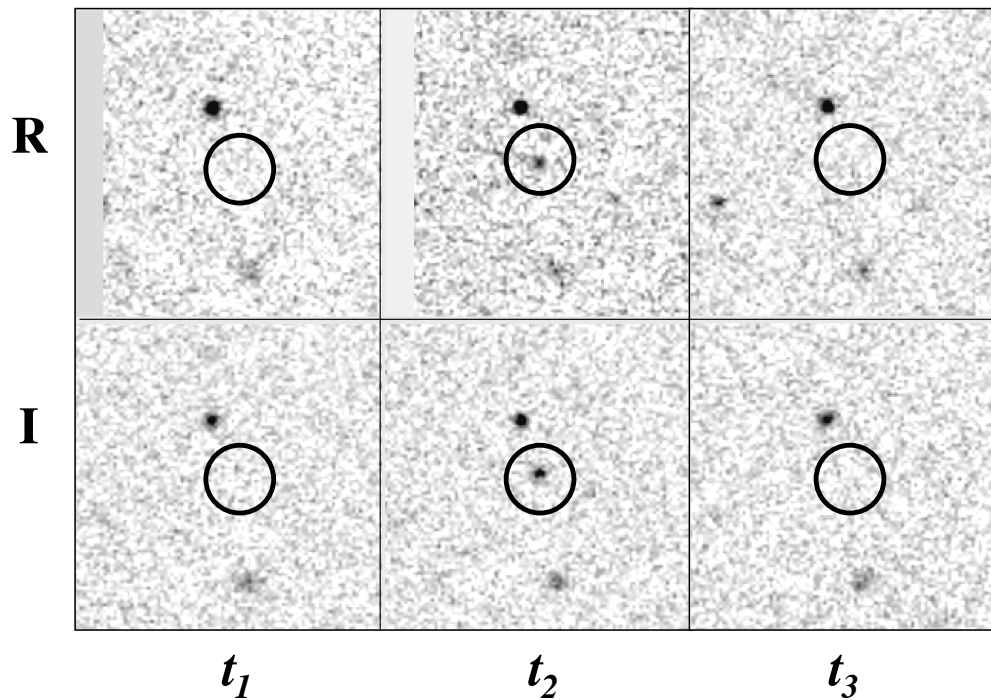
(A. Drake, A. Mahabal, et al.)

From "Morphological Box" to Observable Parameter Space
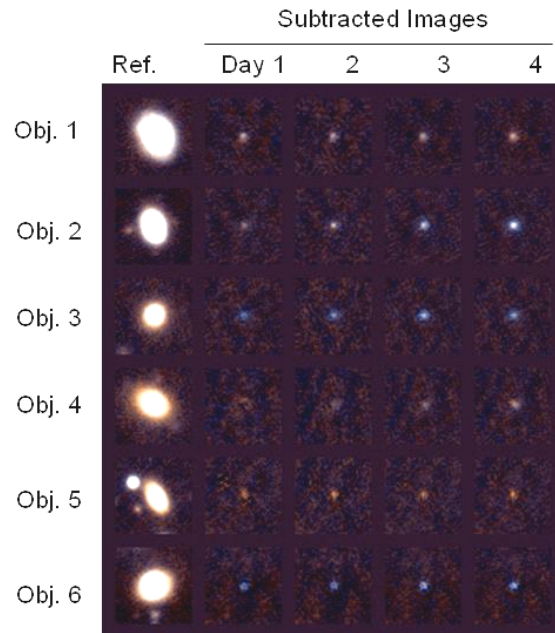

Flux

Non-EM
(ν, GW, CR)

Morphology
parameters

Wavelength

Variability
parameters

Surf. brightness
Contrast

} **Time Domain**

Proper motion

Polarization

Observable parameter space
has many dimensions

RA

Dec
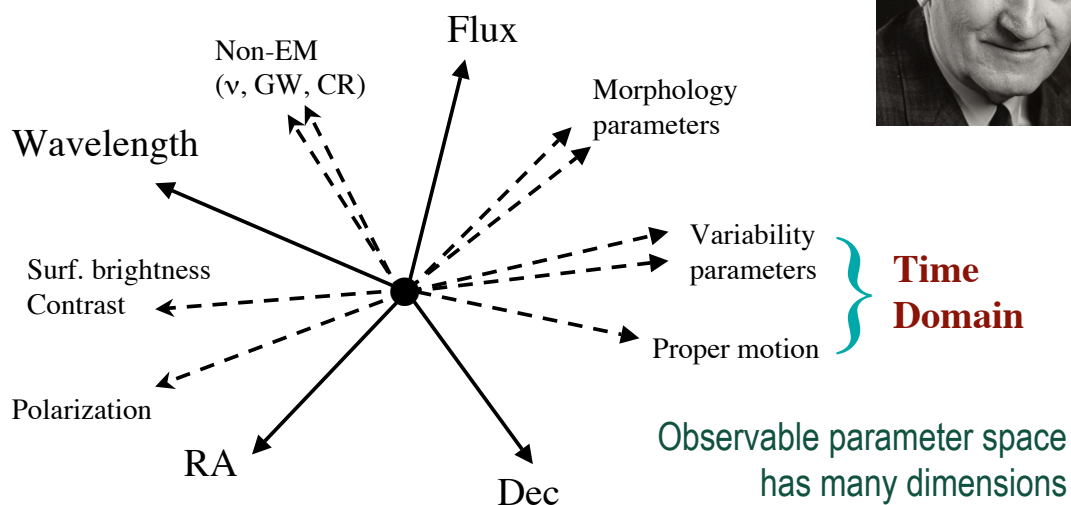
Along each axis the measurements are characterized by the **position, extent, sampling and resolution.** All astronomical measurements span some volume in this parameter space.

Expanding the Observable Parameter Space

Technology advances ➤ Expanded domain of measurements
➤ Discovery of new types of phenomena

(M. Harwit)

As we open up the time domain, we are bound to discover some new things!
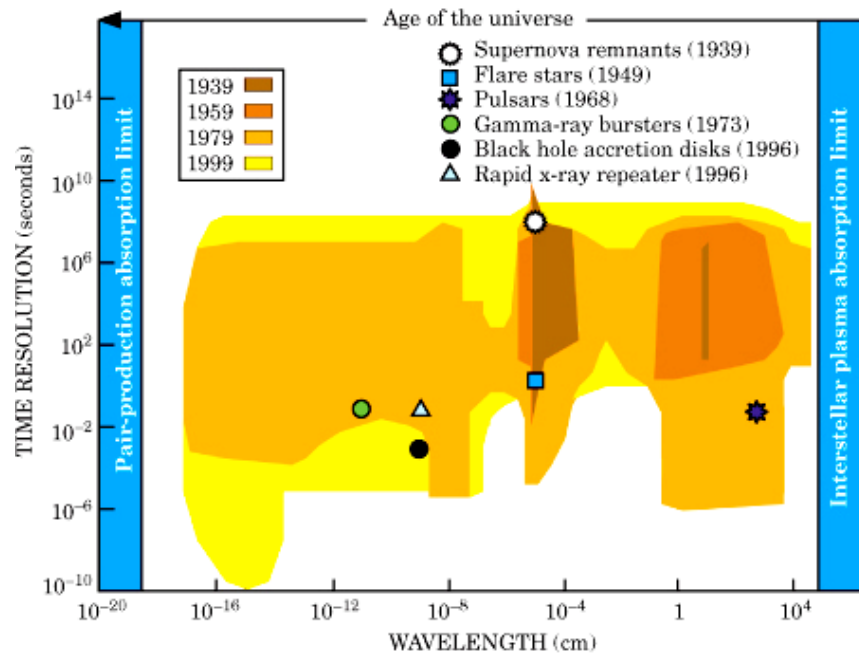
How Quasars Were *Not* Discovered

GQ Comae   **V396 Her**
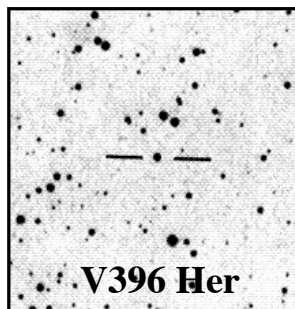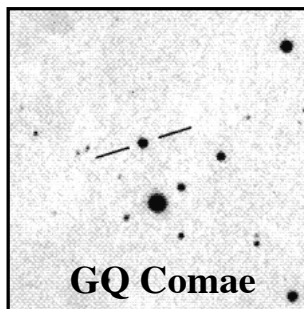
Noted as variable sources even in the 19th century, but …
misclassified as variable stars (e.g., BL Lacertae)

Historical (archival) lightcurve of 3C273, starting from the 1880's …
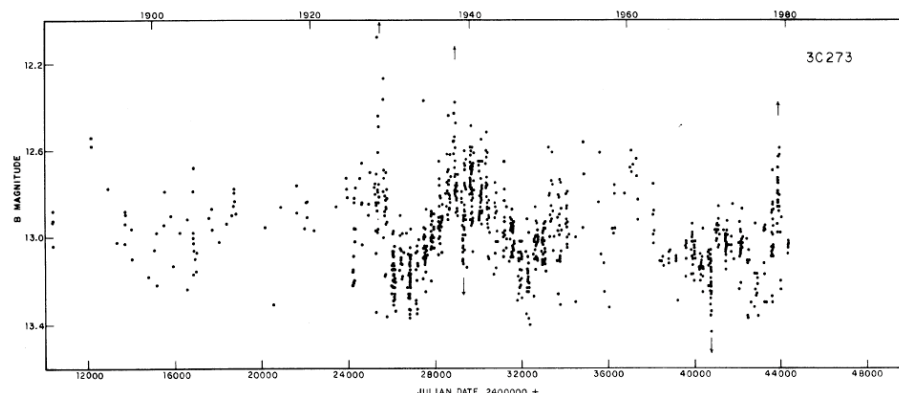
PQ Search for Low-z Supernovae
C. Baltay, P. Nugent, et al. (LBL Nearby Supernova Factory)
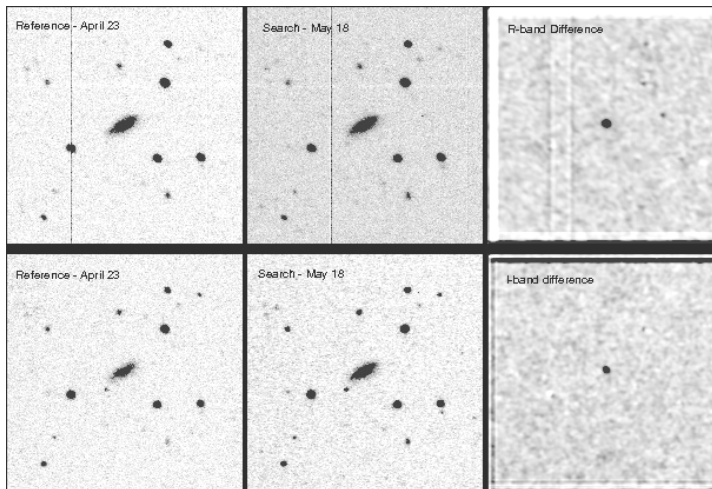
To date, > 500 SNe discovered, including ~ 350 Type Ia, and some peculiar ones

- Calibration of the SN Ia Hubble diagram
- New standard candles from SN II
- Endpoints of massive star evolution
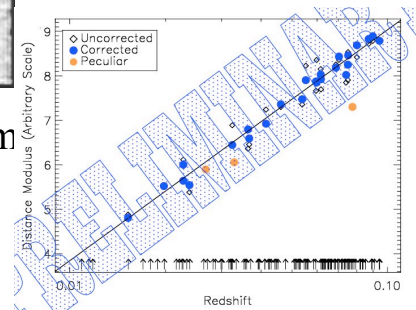
PQ Variability-Selected CVs:

PQV 2254+0742

PQV 2325-0140
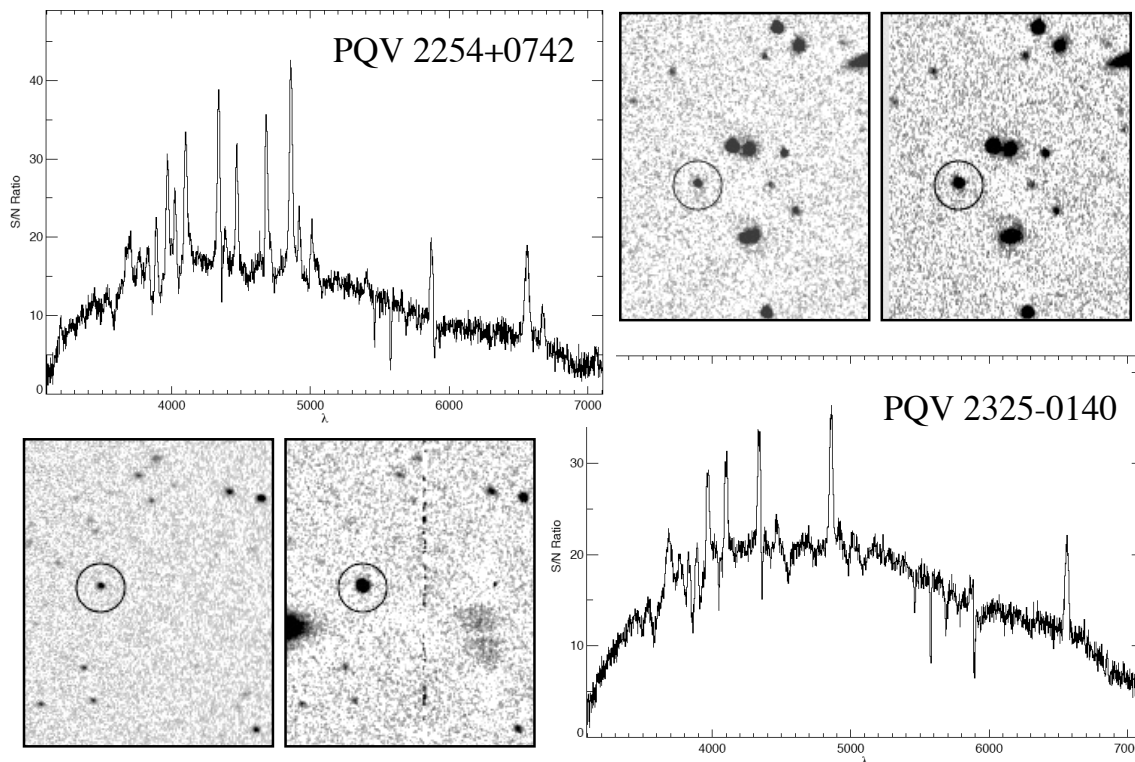
PQ Variability-Selected AGN

Previously unknown
Blazar (radio source):
PQV 2345-1555
(spectrum = continuum)

Previously unknown QSO:
PQV 2321-1448
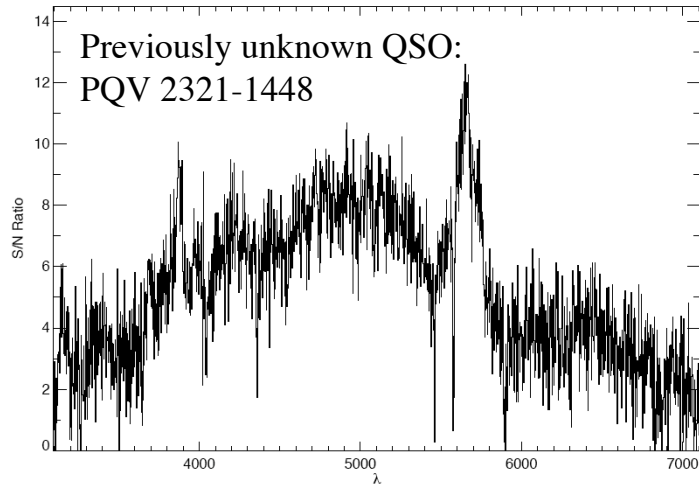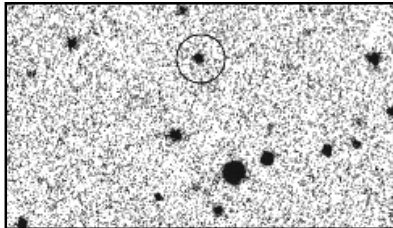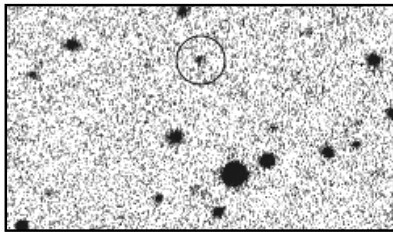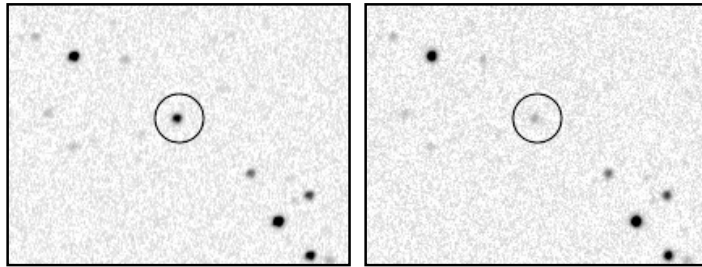
The Variability of Blazars

- Dominated by the jet: instabilities, internal shocks
- Variations in the source luminosity amplified by the relativistic beaming
- Much stronger at the short time scales than the regular, accretion-driven variability of AGN

BL Lac:
20 year
light curves
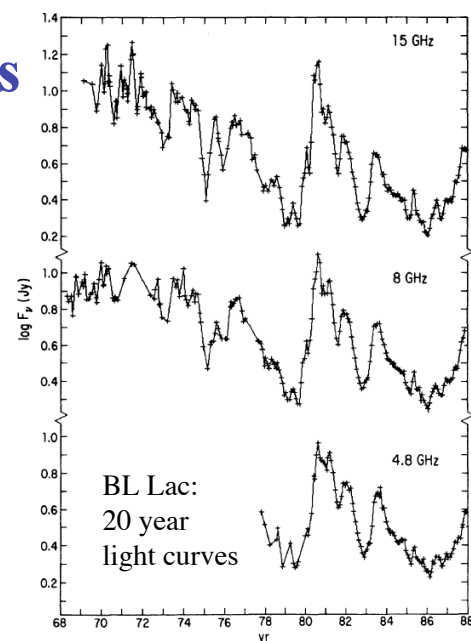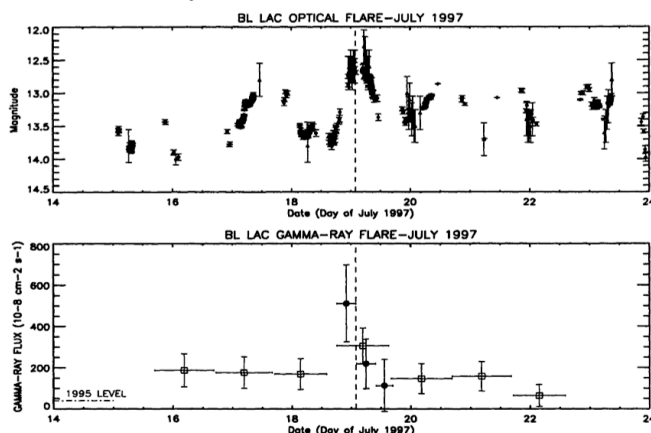
Significant changes seen on time scales as short as hours

← Sometimes correlated optical / γ-ray flares

The Many Uses of Blazars

- AGN demographics and evolution
  - Constraints for AGN unification models
  - Origins of the Cosmic γ-Ray Bgd.
  - Possible new AGN sub-populations?
- Understanding the cosmic accelerators
  - AGN jet origins and their physics
  - The UHECR connection? *Long-term future of particle physics?*
- Astrophysical foregrounds to CMBR fluctuations at high l
- A new probe of the cosmic star formation history, through extragalactic bgd. light as a *f(z)*
  - EBL photon gas is optically thick to high-energy photons

Effect of Extragalactic Background Light

unabsorbed AGN spectrum

AGN at z = 2

AGN at z = 0.5

Integral Flux (counts)

Photon Energy (GeV)
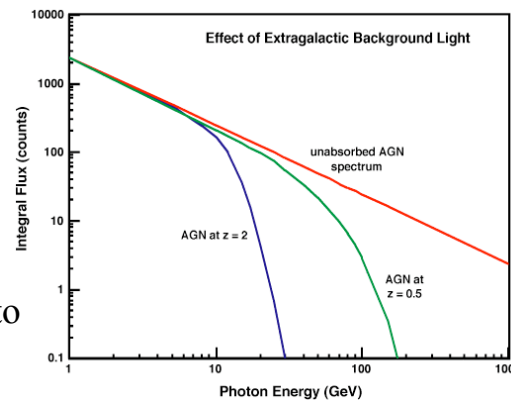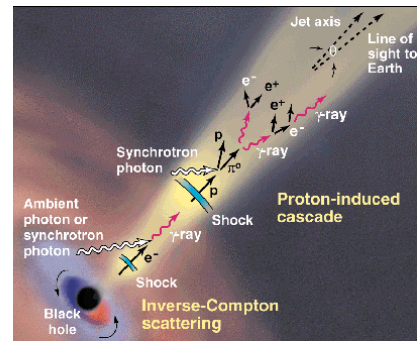
The Cosmic Accelerators: TeV γ-ray Detections of Blazars

About 12 so far. Variability on time scales of minutes implies origin from very compact regions - possibly internal shocks

BL Lac (MAGIC)

PSF

DEC (J2000) [deg]

R.A. (J2000) [h]

PKS 2155-304 (HESS)

Dec (deg)

RA (hours)

Year 96   97   98   99   00   01   02   03

Flux [mCrab]

Mrk 421

Mrk 501

1ES 2344+514

1ES 1959+650

PKS 2155−304

H 1426+428

Date [MJD-50000]
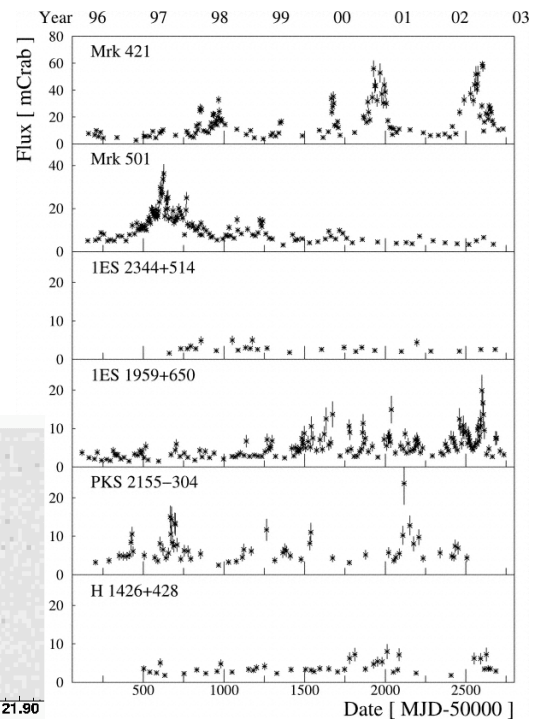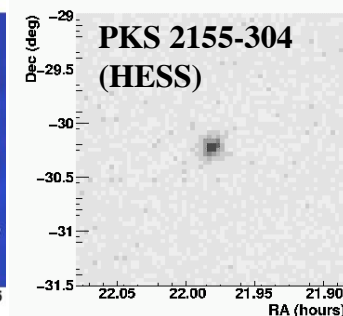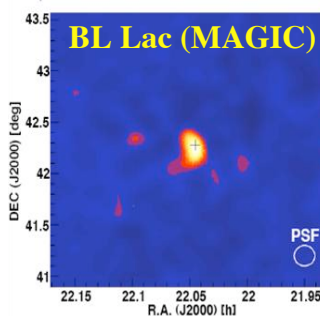
The Cosmic Accelerators: Understanding the Origins of the UHECR Spectrum
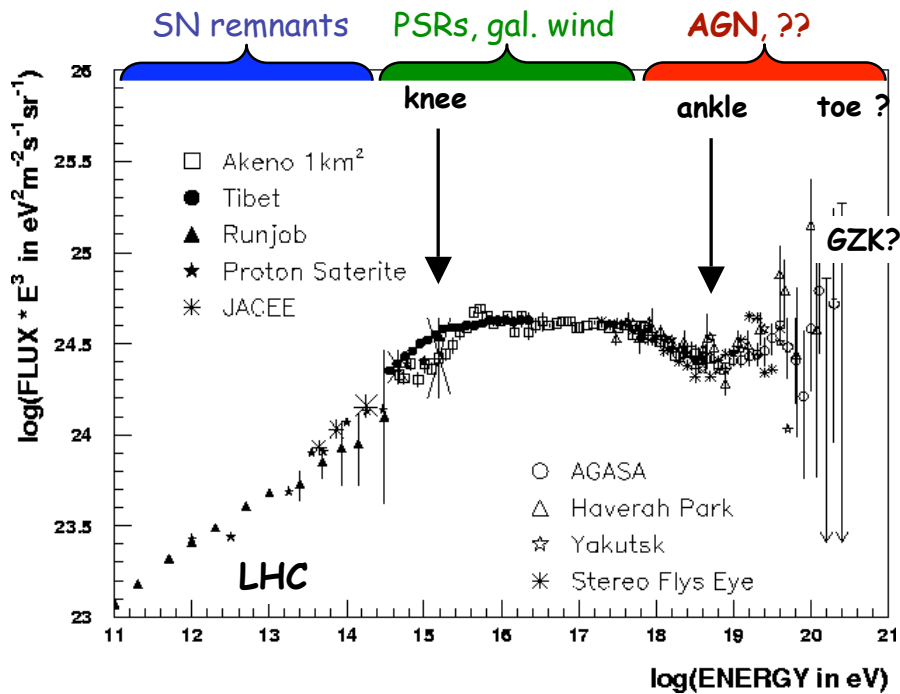
Note: the early *Auger* results
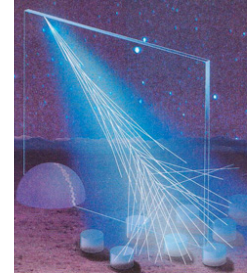
Particle energies $\sim 10^8$ times higher (!) than those in LHC

PQ Variability of AGN and Blazars

- Characterize the high-amplitude variability of known QSOs and Blazars using PQ data
- *Use to devise a pure optical variability (and color?) selection of Blazars*
- Search for highly variable (non-transient) objects and get their spectroscopic IDs
- We recover some known QSOs and Blazars, and find some new ones
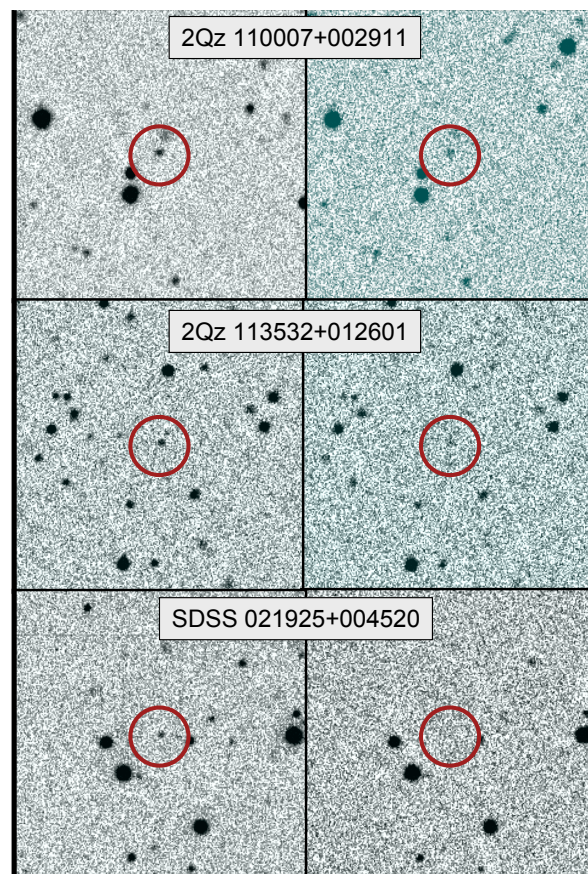
PQ + CSS Archival Light Curves for 3C 454.3

3C 454.3 PQ — 06 Sep 2006 UT

3C 454.3 PQ — 09 Aug 2007 UT

Fermi GST

Milky Way Center · Geminga Pulsar · Vela Pulsar · Crab Pulsar · Blazar 3C454.3

First observation = 4 aug 2002
Last observation = 22 jun 2008

PQ

CSS
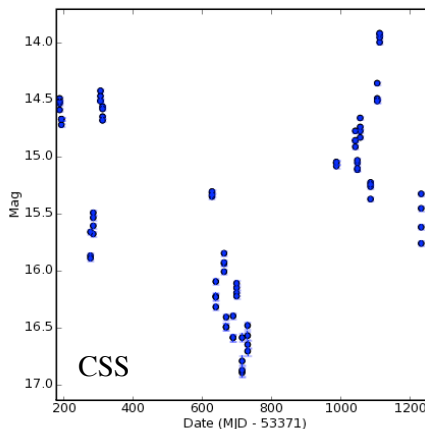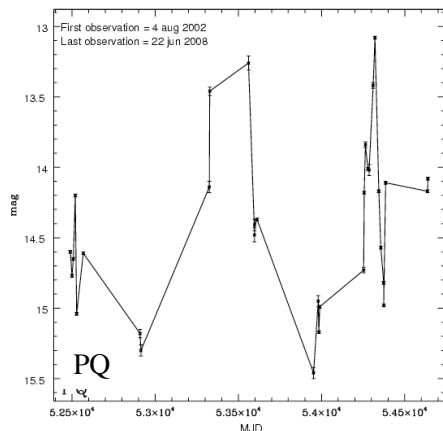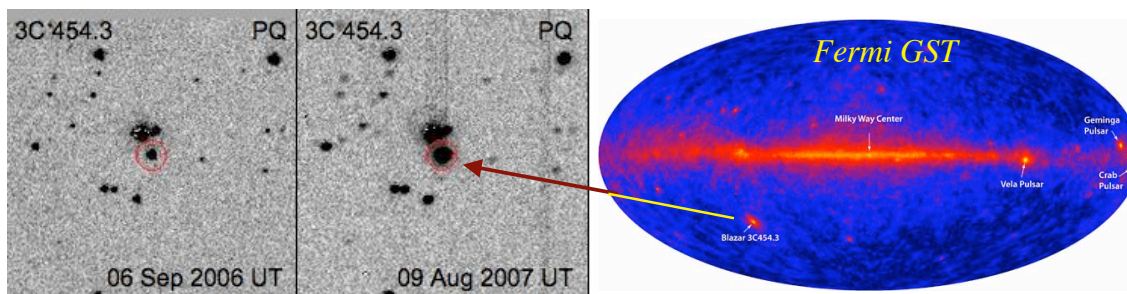
A total of 155 exposures on 54 dates, time baseline ~ 6 years

Thousands more blazar light curves to come…

CMB Foreground Radio Sources

Flat-spectrum foreground radio sources detected in WMAP data

(Chen & Wright 2008, Wright et al. 2008)
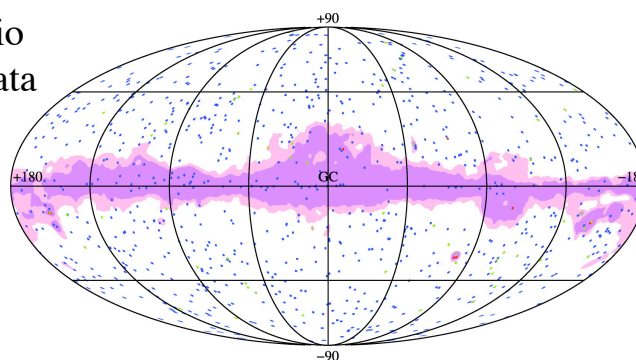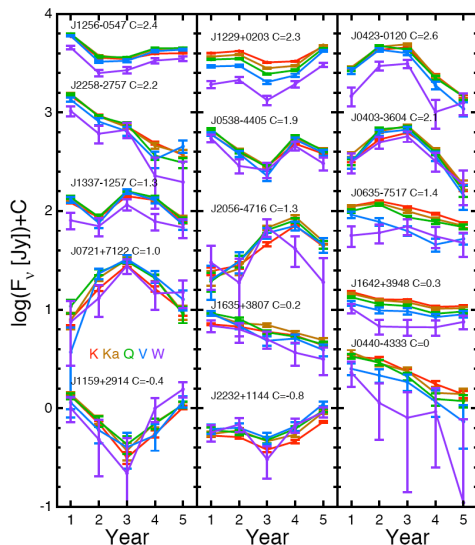
- All are likely **blazars** (FSRQ)
- All seem to be **highly variable**
  - Characterize their optical variability
- Some are unidentified, and some may be mis-identified
  - Look for purely variability-based IDs
- Understanding of this population is essential for CMBR cosmology at high angular frequencies, e.g., with *Planck*

A Variability-Selected ID for an Unidentified WMAP Source

(Presumably a Blazar/FSRQ)

(Morton et al. 2008, in prep.)

WMAP error circle: ~4'
Unidentified source WMAPJ1628-0903

WMAPJ1628-0903: 514

First observation = 1 jun 2002
Last observation = 30 may 2008
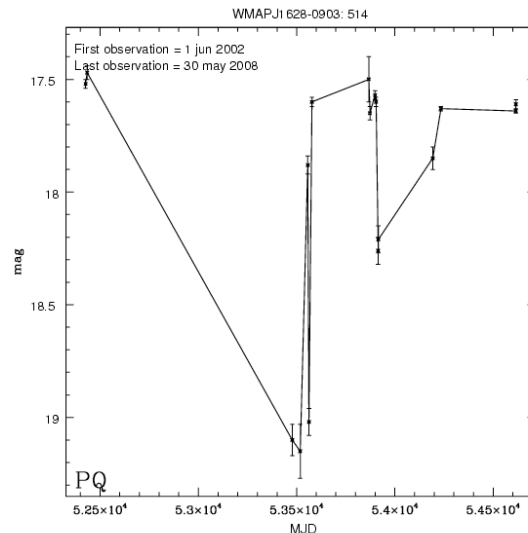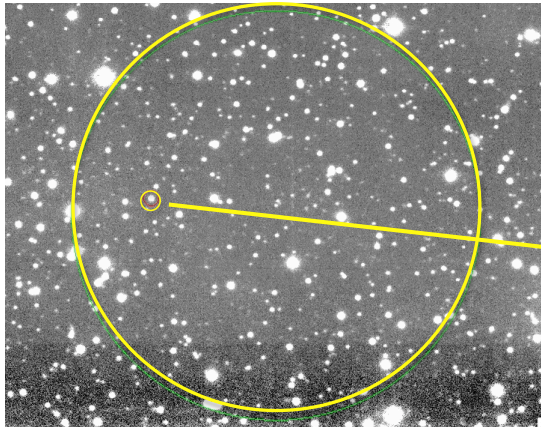
Brightens by ~1.5 mag in one day!
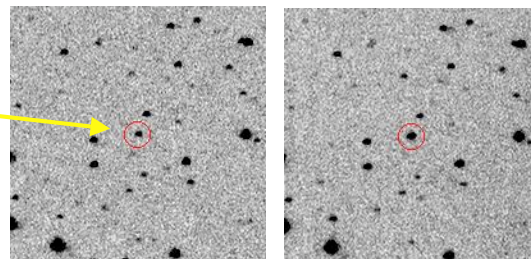
29 Jun 2006   mag=19.12   30 Jun 2006   mag=17.45

The Palomar-Quest Event Factory

Detect ~ 1 - 2 $\times 10^6$ sources per half-night scan

Compare with the baseline sky

Find ~ 10^3 apparent transients (in the data)

Remove instrum. artifacts

Identify ~ 2 - 4 $\times 10^2$ real transients (on the sky)

Remove asteroids

Identify ~ 1 - 10 possible Astrophysical transients

Classification and follow-up

tonight   baseline

R

I
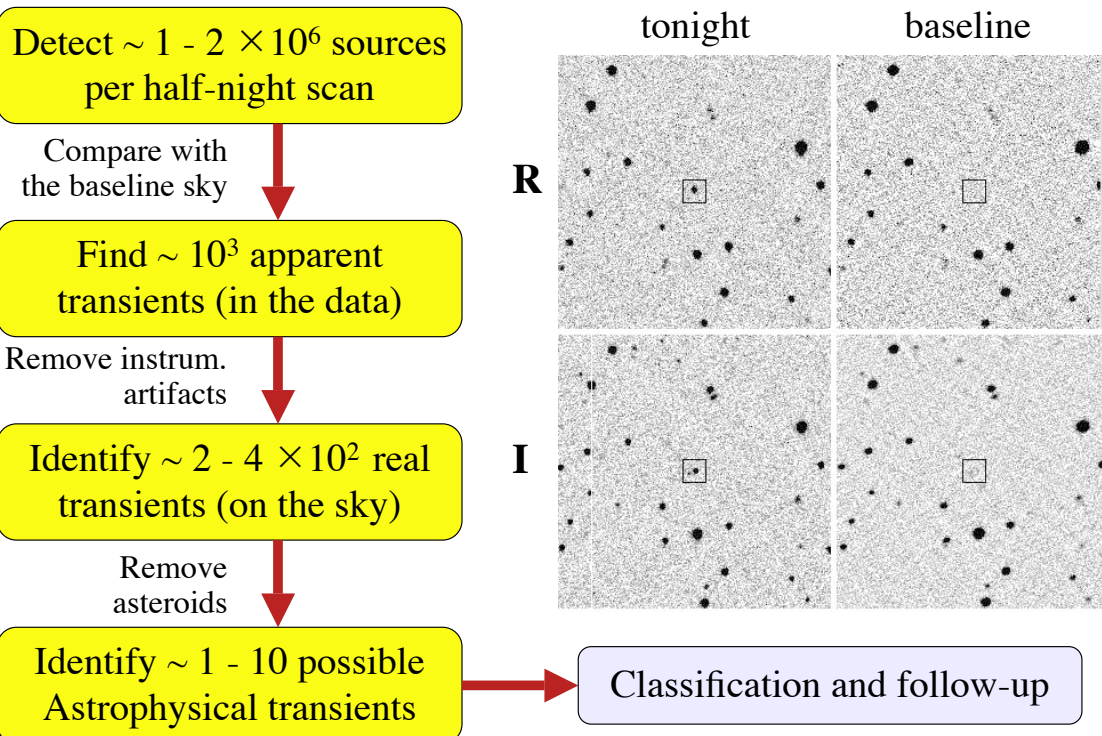
Asteroids: The Main Contaminant

- The vast majority of "transient" detections are *mostly asteroids*
- We find ~ **1 - 3 asteroids / deg^2** down to ~ 20 - 21 mag, at moderate ecliptic latitudes
  - ✗ Only ~ 50% are previously known
  - ✗ **They outnumber the astrophysical transients by a factor of ~ 10^2 - 10^3 !**

Mitigation:
- Optimized cadence: scan and rescan ~ 1 - 4 hours apart
- Crossmatch to asteroid DB's (HORIZONS, IMCCE)
- Improved proper motions and colors

Sometimes they overlap stars:

PQ Real-Time SN Discoveries

P200 spectroscopy within an hour of initial detection: Young SNe Ia

PQOT024105−033814

PQOT230627+095342

PQV224527+103932
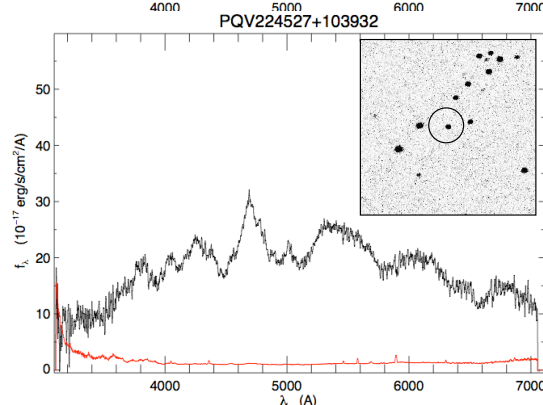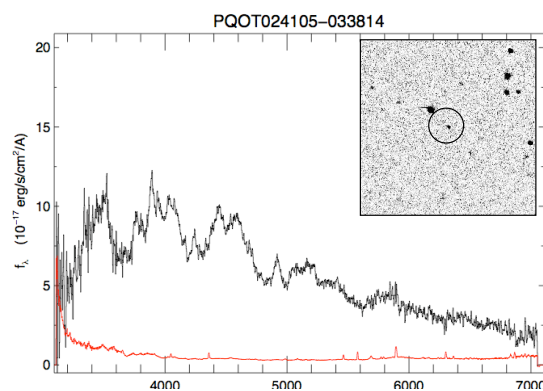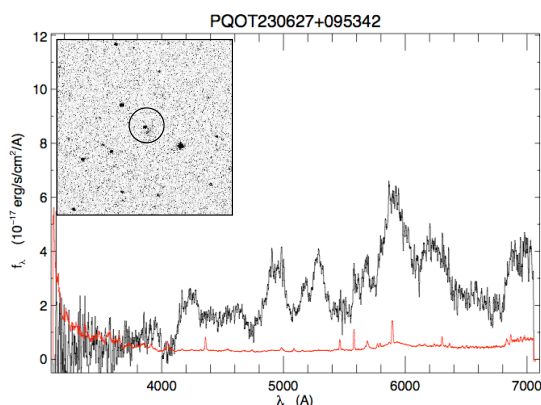
PQT 080119:091534+081356 - A Dwarf Nova

Baseline

Discovery

SDSS

g = 17.6 mag,
r = 17.7 mag

SDSS counterpart:
g = 22.8 mag,
r = 23.0 mag

P200 spectrum (G. Herczeg)
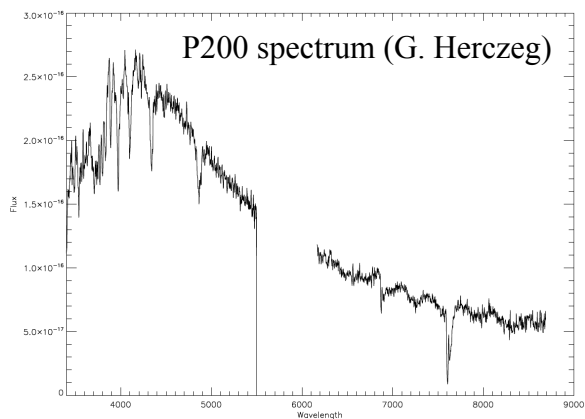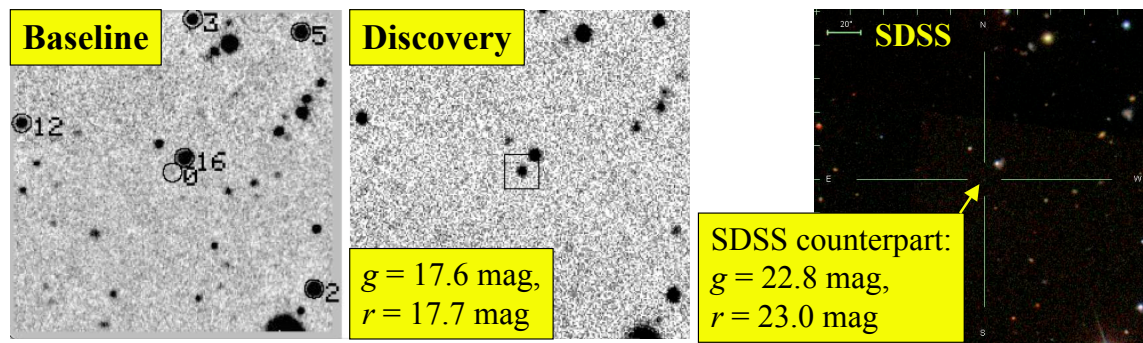
*Donalek et al. ATel 1362,
Glikman et al. ATel 1367*

Jan. 20   Jan. 31

P60
follow-up
(Mahabal
et al.)
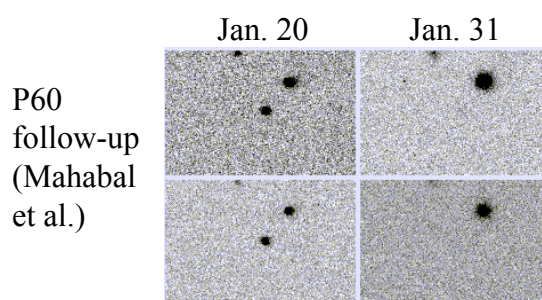
PQ Real-Time Discovered AGN

PQT 071010:034520-012111
Blazar

real-time   baseline

PQT 071011:031515-034914
QSO, z = 1.26

real-time   baseline

g

r

i
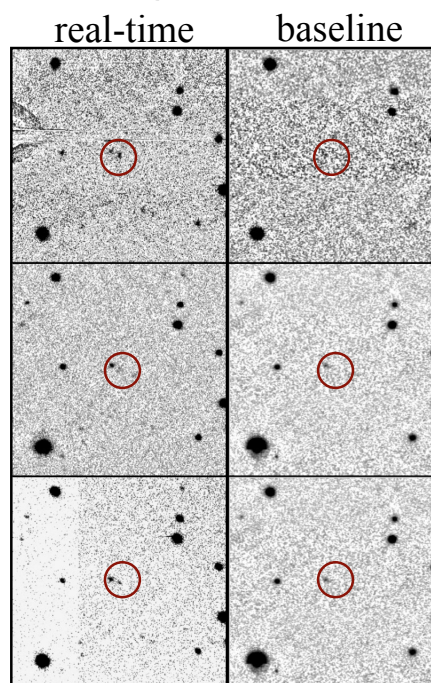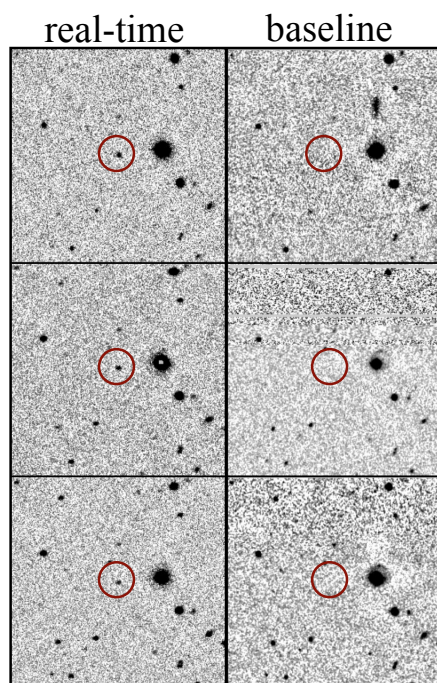
Catalina Real-Time Transient Survey

CSS is a search for NEOs, led by S. Larson, E. Beshore, et al. (UAz LPL). The survey uses the 24-inch Schmidt on Mt. Bigellow, and a single, unfiltered 4k×4k CCD (and also telescopes at Mt. Lemmon and Siding Spring). Limiting mag ~ 19.5, Coverage ~ 1000 deg^2/night
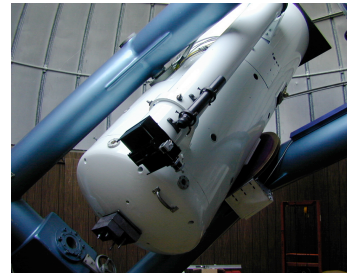
We are processing their data stream to look for astrophysical transients

Fast transient (a flare star), CSS080118:112149–131310
4 individual exposures, separated by 10 min
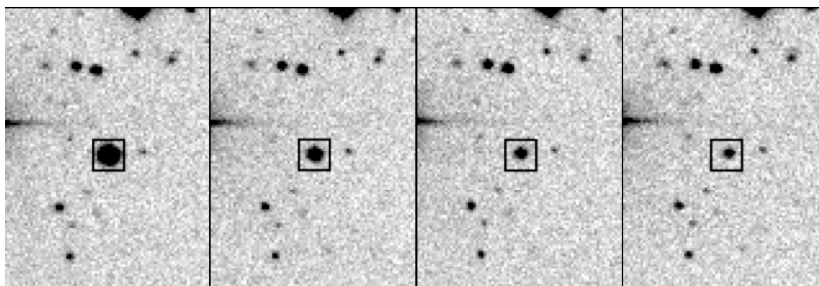
Light curve
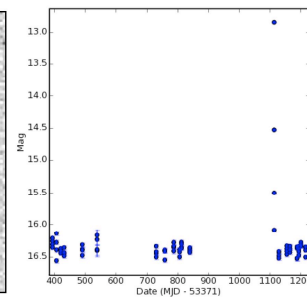
Early Results from CRTS

In the first ~ 6 mos. of operation:
- Over 500 confirmed transients discovered
- Covered the cummulative area > 450,000 deg^2
- About 100 SNe, including some ultraluminous ones
- Over 60 new CVs, plus many known ones
- Many blazars, flaring stars, etc.

A significant population of SNe in faint host galaxies; complements other surveys

Discovery   Baseline
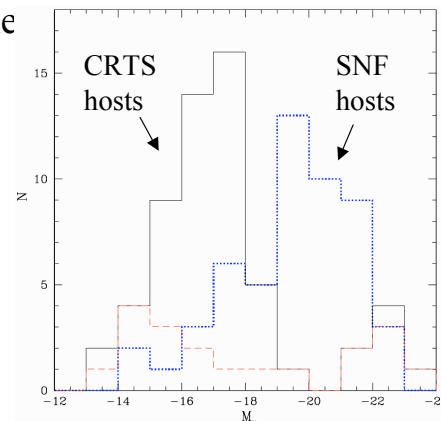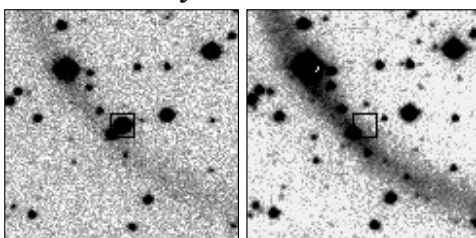
CSS 071218:120153-185822 = SN 2007sr: SN Ia in the Antennae merger

Scientific Measurement Cycle

Typically it looks like this:

Characteristic time scales
typically ~ a *year*
(or at best, days)

Obtain some measurements

Analyze and interpret the data

Decide on optimal follow-up measurem. Propose/implement
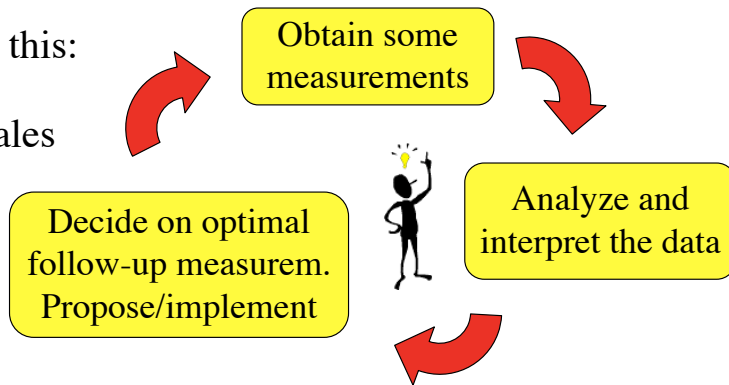
But what if the
phenomena we study last/change on time scales of *minutes/hours*?
… and the data rates are measured in TB's per day or higher?
… and the measurement, data, computation assets are distributed?
What is required is a system which is:

- Fully automatic/robotic, with no humans in the loop
- Draws on a number of important computational technologies

The VOEventNet Project

PI: R. Williams

- A telescope sensor network with a feedback
- Scientific measurements spawning other measurements and data analysis in the real time
- Please see **http://voeventnet.caltech.edu**

External archives — NVO
Compute resources
Robotic telescope network

P48 → **PQ Event Factory** → **VOEN Engine**

P60
Raptor
Paritel

Web Event Archive ↔ Follow-up obs.
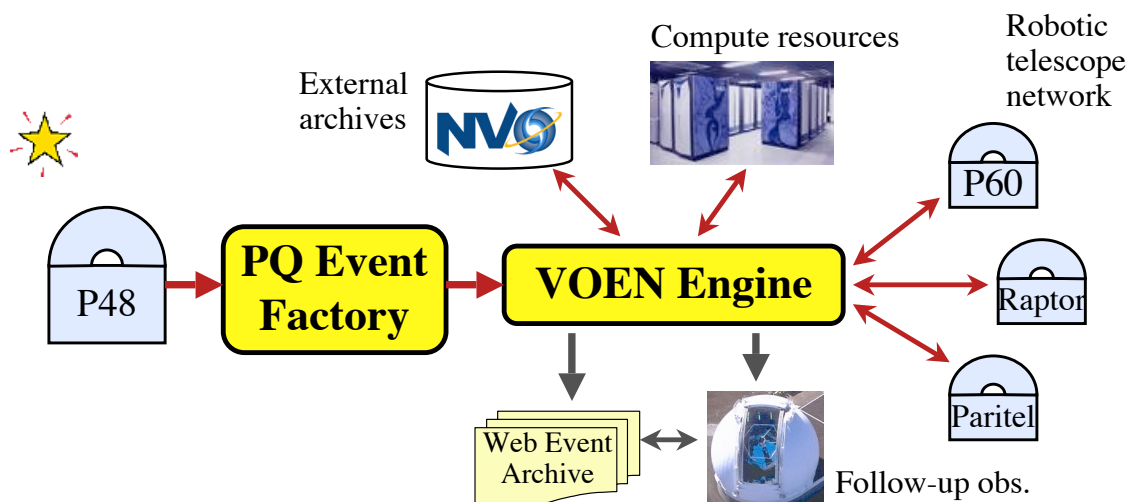
VOEventNet Real-Time Event Publishing

- Ingesting and distributing multiple even streams: GCN, PQ, CSS,…
- Events published on the web, RSS feed, Jabber, and Google Sky

voeventnet.caltech.edu

- Home
- Project Description
- Personnel
- GCN VOEvents
- SDSS Supernovae
- ESSENCE Supernovae
- OGLE Microlensing
- PQ Transients
- Transients in the Griffith Park "Big Picture"
- IVOA VOEvent pages
- Search the Nexus
- Subscribe
- Wiki

VOEventNet: Real-Time Astronomy with a Rapid-Response Telescope Grid

VOEvents from the Palomar Quest Transient Search

- This page is generated automatically as incoming PQ events are received and was last updated at
- Additional information about PQ Transients that are available here .
- Information on subscribing to receive PQ Transients and other VOEvents in **real time** is here:
- A near real time feed is available here: XML RSS
- This table contains information about Transients obtained from PQ (Table Help).

Palomar Quest Events

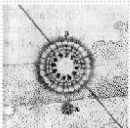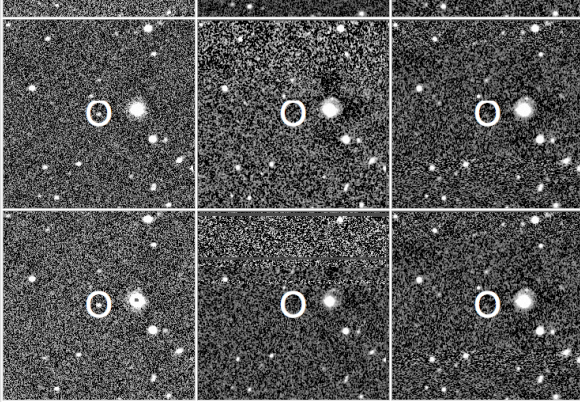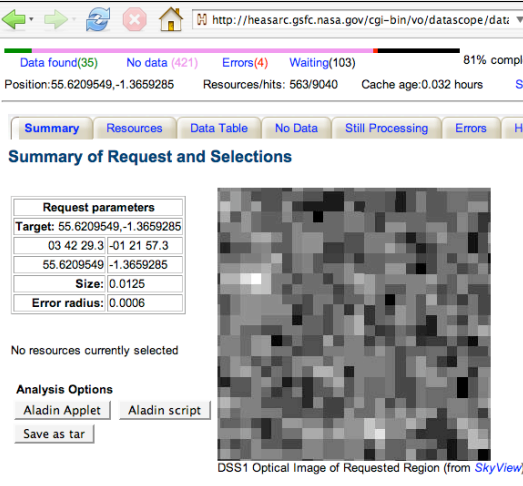| ID	Alert Time (UT)	Event Time (UT)	RA (deg)	Dec (deg)	Error
7052101243010670393	2007-05-21T08:43:11	2007-05-21T07:06:38	234.5119299	15.9229255	2.16
7052101243030690374	2007-05-21T08:43:09	2007-05-21T07:11:12	235.7001958	15.5061457	2.16
7052101233260390193	2007-05-21T08:43:07	2007-05-21T05:56:58	217.9791300	11.6790801	2.16
7052101243170240345	2007-05-21T08:43:06	2007-05-21T05:21:33	208.2908345	13.1145446	2.16
7052101243030690374	2007-05-21T07:26:34	2007-05-21T07:11:12	235.7001958	15.5061457	2.16
7052101243010670393	2007-05-21T07:16:57	2007-05-21T07:06:38	234.5119299	15.9229255	2.16
7052101243090550350	2007-05-21T06:47:02	2007-05-21T06:36:37	226.9676221	14.4591642	2.16
7052101233260390193	2007-05-21T06:36:53	2007-05-21T05:56:58	217.9791300	11.6790801	2.16

Automatically Generated Image Cutouts and Coadds, Webpages for Each Event

ID = 7101001343110540076
newast = 0.000000
av_motn = 0.017245
av_deltime = 8.081280
av_uncertx = 0.050421
av_uncerty = 0.049168
av_inclin = -134.201264
Time = 2454383.917890

⬅ Human-readable relevant event data

Automated Links to VO Data Resources

Dynamically updated, used as an input to event classifiers

Building a Better Baseline: HyperSky

The next generation scientific sky atlas

Dynamical, evolving, multi-layer, multi-epoch, federated data set + On-demand computed custom data products
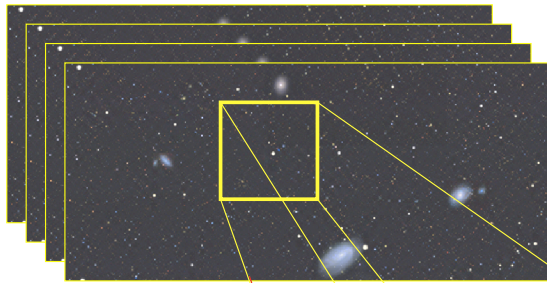
Panoramic imagery from different sky surveys (e.g., DPOSS, SDSS, PQ, 2MASS, …) + extracted source catalogs and metadata, identified by a time epoch, bandpass, seeing, etc.

Optimized coadd of selected images (e.g., by bandpass, time interval, seeing, S/N…) + source catalogs *+ flux time histories (variability)* for each source + linked information

Use this ➤
for comparison
with tonight's data

The HyperSky Conceptual Architecture

- A modular, dynamical system for analysis, data mining, and follow-up of large synoptic sky surveys
- Builds on the existing foundations from VO, etc.
- Real-time and archival data exploration

Input Data and Event Streams

Local Cached & Staged Data Resources

External Distributed Data Resources

NVO

External Compute Resources (Web svcs., Grid/Cloud)

Local Compute Resources

Selected Follow-up

VOEvent Distribution

Workflow Bench / Process Staging & Control

Event Detection

Event Characterization

Event Classification

Event Publishing

Real-Time Users

Archival Users

Event Archives

Towards Event Portfolios

A system to capture and organize heterogeneous data and information on astronomical events, using semantic web technologies

(M. Graham & R. Williams)

Input into event classifiers and other scientific analysis
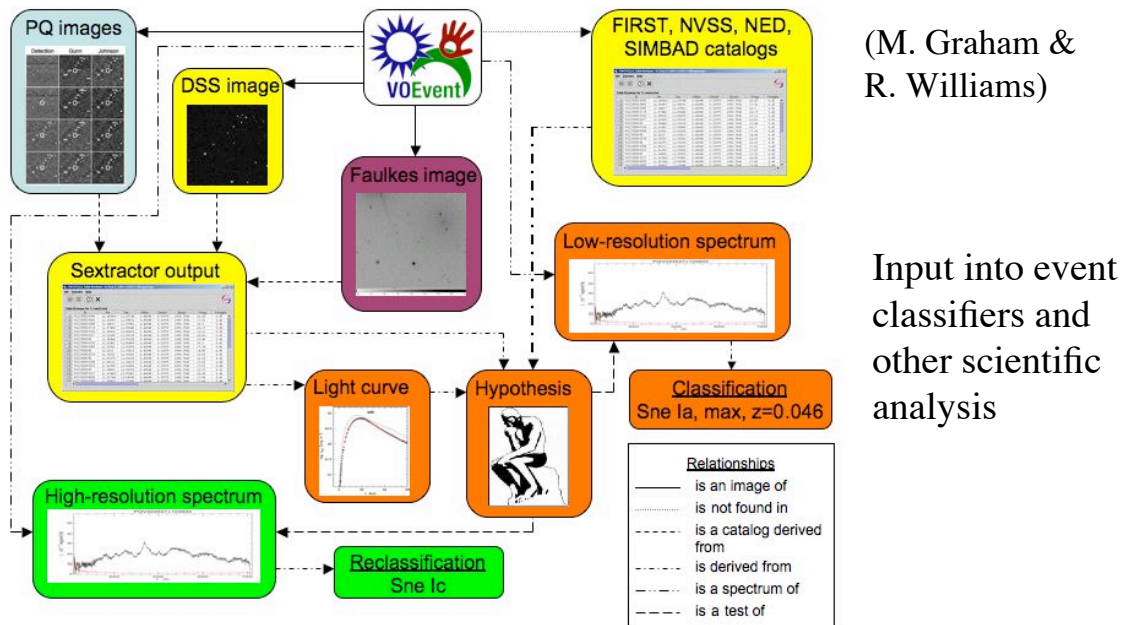
Towards Automated Event Classification

A **necessity** for large synoptic surveys

Classification probabilities (evolving, iterated)
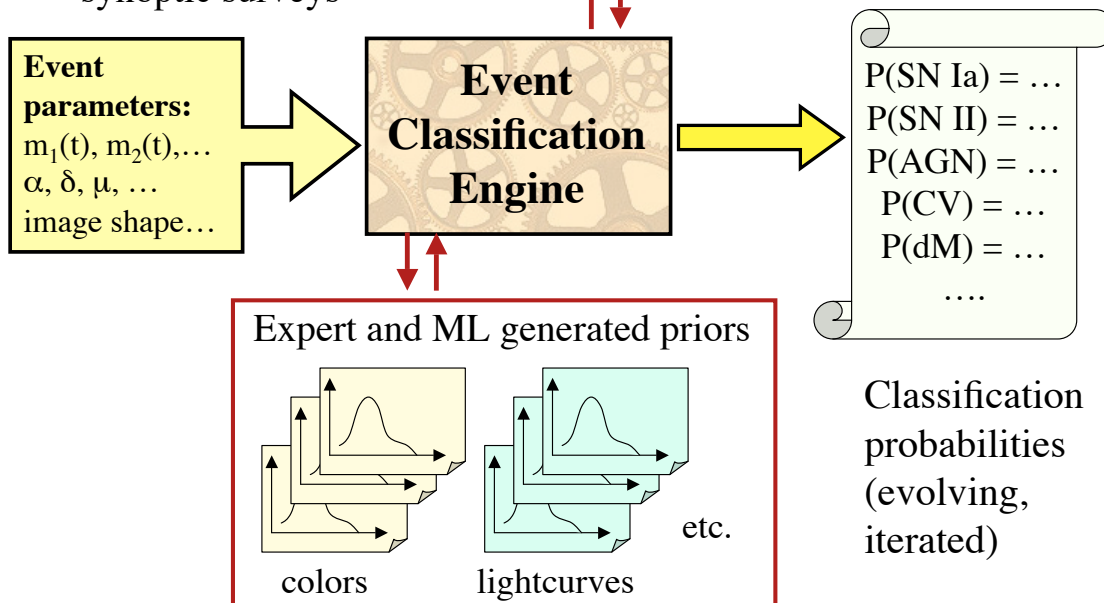
Bayesian and Machine Learning Event Classification

In collaboration with M. Turmon, J. Jewell, et al. (JPL)

Work in progress…
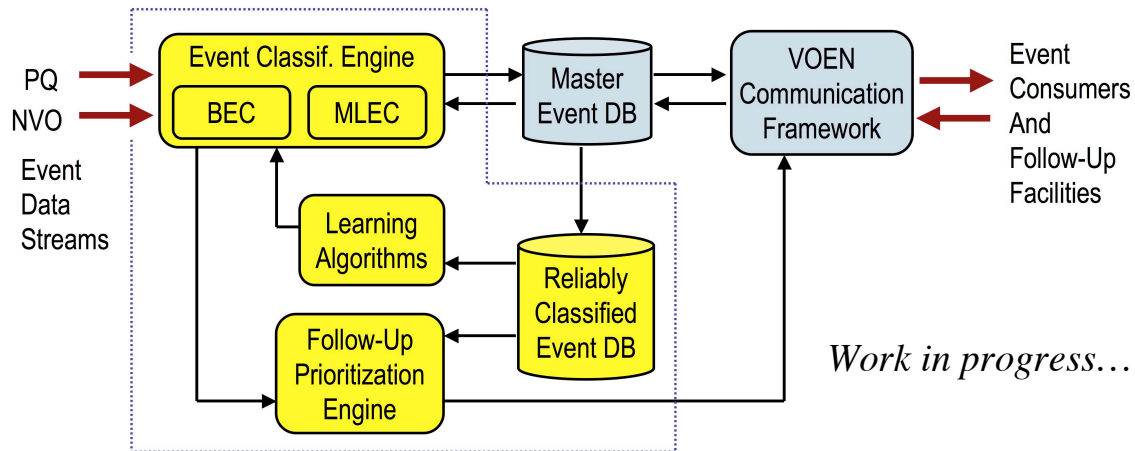
- Bayesian methods are more tolerant of heterogeneous or missing data; easy to add new event classes
- Machine learning approach (ANN and SVM, unsupervised classif.) will get better as the database of known events grows

Automating the Optimal Follow-Up

What type of follow-up data has the greatest potential to discriminate among the competing models (event classes)?

Request follow-up observations from the optimal available facility
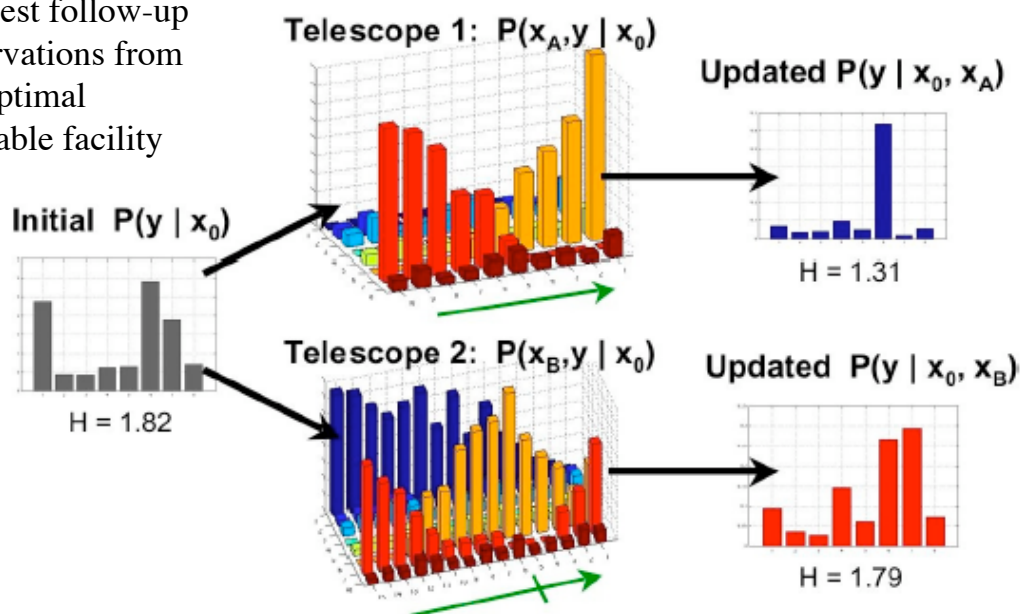
The (Tsunami) Wave of the Future

- Now: data streams of ~ **0.1 TB / night, ~ 10 - 10^2 transients / night** (SDSS, PQ, various SN surveys, asteroid surveys)

- Forthcoming on a time scale ~ 1 - 5 years: ~ **1 TB / night, ~10^4 transients / night** (PanSTARRS, Skymapper, VISTA, VST…)
- Forthcoming in ~ 5 - 10 years: LSST, ~ **20 TB / night, ~ 10^5 - 10^6 transients / night**

  } **A major, qualitative change!**

- Observational follow-up needs:
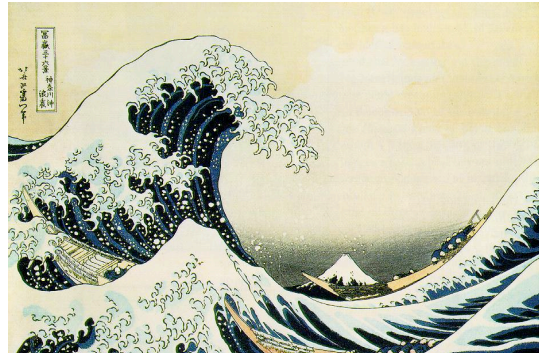 - Rapid photometric/positional monitoring
  - Rapid spectroscopy
  - Information/computation infrastructure

  } *Transient classification technologies are essential*

Some Things We Have Learned

- In a single-pass, there are ~ 10^{-2} transients/*deg*^{2} down to ~ 20 mag at moderate/high Galactic latitudes
- There are ~ 10^2 - 10^3 asteroids for each astrophysical transient
  ➡ *A joint asteroid / transient analysis is necessary*
- Most of the transients are known types of objects, mainly CVs and SNe, with some AGN and flaring stars
  - Apossibility of new types of objects or phenomena is still open
- The quality of the ***baseline/fiducial sky*** is a key issue
  - It must be deep, clean, complete, and wavelength-matched, and dynamically evolving
- *Rapid follow-up is necessary* in order to understand the transients: lightcurves, colors, spectroscopy, other λ's
- Next-night science is *much* easier than real-time

Software, Software, Software!

- All data-intensive projects are primarily software projects. Plan costs, development accordingly
  - You can leverage a lot, but you will still be writing lots of software
- Striking the optimal balance between completeness and contamination is very hard ☯
- In a massive data stream, and a complex software system, most unlikely things will happen, and most of them are bad
- Lots of different kinds of artifacts can initially look as transients. You can filter them out, but it takes some work.
- There is a tension between the real-time processing demands, and non-time-critical processing and archival operations. Data flows and databases and survey operations should be designed with this in mind.

The Time Domain Astronomy (TDA)

- Data fusion (multi-epoch, multi-wavelength, contextual,...) is a key for interpretation and understanding of TD phenomena
  - A survey optimized for a maximum event discovery rate cannot be also efficient for a self-follow-up
  - Dedicated follow-up facilities are a must
  - Spectroscopy is the key bottleneck, and this will get worse
- The same data stream can feed multiple scientific studies
  - However, specialized surveys/experiments are optimized for discovery of particular types of phenomena; their cadences, depths, bandpasses, etc., represent observational filters which may preclude discoveries of different and new types of phenomena
- TDA is an inherently *an astronomy of telescope systems*, and it requires a *strong computational/informational infrastructure*
  - Automated event classification is an essential technology
  - TDA is the "killer app" of Virtual Observatory